MEASUREMENTS OF THE FLUX OF LOW-ENERGY SOLAR-FLARE POSITRONS

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We report new upper limits to the flux of solar-flare positrons in the energy range 0.2 - 2 MeV. The observations were made during four solar-particle events in late 1972, with the Caltech Electron/Isotope Spectrometer on IMP-7. The 0.2 - 2 MeV positron flux is compared directly to the solar-flare electron (0.2 - 2 MeV) and proton (1.2 - 27.5 MeV) fluxes measured in the same detector system. Summing over four solar events, we find $e^+/(e^+ + e^-) < 6 \times 10^{-3}$. Calculated fluxes of solar-flare positrons for these four events are well below our upper limits.

1. Introduction. Chupp et al. (1973) have reported the identification of a line flux of 0.5 MeV γ-radiation during the large solar particle events of August 1972. These observations imply the existence of appreciable numbers of solar positrons during periods of intense solar activity, presumably the products of nuclear interactions of flare accelerated particles with the ambient solar atmosphere. Lingenfelter and Ramaty (L&R) (1967), and Ramaty and Lingenfelter (R&L) (1973) have considered in detail positron production and annihilation during solar flares. For solar-energetic-particle spectra typical of those observed at Earth, they find the dominant positron source to be the β^+ decay of nuclear interaction products such as ^{11}C, ^{13}N, and ^{15}O. Table I, from R&L (1973), summarizes data on these positron production mechanisms. Note that the positron β^+ decay energies are within the 0.2 - 2 MeV range covered by this experiment. A second source of positrons at higher energies (~ 10 - 100 MeV) is π-μ-e decay. These positrons would not make significant contributions to our energy interval unless there are significant energy-loss processes at work.

Although the intensity of the 0.5 MeV line observed on August 4 and 7 can be directly related to the rate of positron annihilation on the sun during these periods, additional assumptions are required to predict the number of positrons escaping into interplanetary space. R&L (1973) consider two limiting cases. If the positrons result from the interactions of energetic particles moving downward into the sun (thick target model), energy-loss and magnetic field considerations suggest that few of the ~ 1 MeV positrons would escape from the sun.

If, however, the positrons are produced by the interactions of accelerated particles as they leave the sun, and if the amount of matter traversed is small (thin target model), it is possible that a significant fraction of the ~ 1 MeV positrons produced may escape. Notice in particular that approximately one-half of the positron-producing reactions will involve accelerated CNO nuclei impinging on ambient solar hydrogen. Since the resulting secondary

TABLE I

POSITRON PRODUCTION MECHANISMS

β^+ Emitter and Decay Mode	Maximum Positron Energy (MeV)	Half-life (min)	Production Modes	Production Threshold Energies (MeV/n)
$^{11}C \rightarrow {}^{11}B + \beta^+ + \nu$	0.97	20.5	$^{12}C(p,pn)^{11}C$	20.2
			$^{14}N(p,2p2n)^{11}C$	13.1
			$^{14}N(p,\alpha)^{11}C$	2.9
			$^{16}O(p,3p3n)^{11}C$	28.6
$^{13}N \rightarrow {}^{13}C + \beta^+ + \nu$	1.19	9.96	$^{14}N(p,pn)^{13}N$	11.3
			$^{16}O(p,2p2n)^{13}N$	5.54
$^{14}O \rightarrow {}^{14}N + \beta^+ + \nu$	1.86	1.18	$^{14}N(p,n)^{14}O$	6.4
$^{15}O \rightarrow {}^{15}N + \beta^+ + \nu$	1.73	2.07	$^{16}O(p,pn)^{15}O$	16.54

^{11}C, ^{13}N, and ^{15}O nuclei have half-lives of several minutes (Table I), they may very likely be well into interplanetary space before they decay. In this case the number of positrons in interplanetary space will be a function of the number of CNO nuclei in the flare, and the mean pathlength (g/cm^2) traversed during acceleration. We also see from Table I that these positrons will be accompanied by the isotopes ^{11}B, ^{13}C, and ^{15}N. Since it is safe to assume that any ^{11}B observed is of secondary origin, simultaneous measurements of solar-flare positrons and ^{11}B would be important. Thus it is evident that the observation of solar-flare positrons would provide significant information for studying a variety of solar-flare features.

2. The Instrument. The observations reported here were made with the Caltech Electron/Isotope Spectrometer (EIS) which was launched on IMP-7 in September 1972. The detector system, shown in Figure 1, consists of a stack of eleven silicon surface-barrier detectors surrounded by a plastic-scintillator cup. Detectors D0, D1, D3, and D4 are annular devices. All silicon detectors except D2 have nominal thicknesses of 1 mm and thresholds of ~ 160 keV, and are thus fully sensitive to penetrating minimum-ionizing particles.

The EIS has two modes of charged particle detection relevant to the present discussion. In the Narrow Geometry mode, the four annular detectors act as an active collimator, and we analyze events in detectors D2, and D5 through D9. The 50 μm detector, D2, allows clean electron-nuclei separation. This mode is given highest priority, and dominates the analysis in the presence of intense particle fluxes. In the Wide Geometry mode we analyze events which trigger D0 without penetrating to D10 or D11. The measurement of electrons and nuclei with this detector system is discussed in more detail in Hurford et al. (1973a, 1973b).

Positrons are identified by detecting their annihilation γ-radiation, as illustrated in Figure 1. If an incident positron stops in D0, one of the 0.51 MeV annihilation γ-rays may Compton scatter in another detector such as D6, D7, D8, or D9. Thus, the coincidences D0D6, D0D7, D0D8, or D0D9, in anticoincidence with all other detectors, would be positron signatures. Higher energy positrons (≳ 1 MeV) produce events with, for example, D0D1D6 signatures. In the Narrow Geometry mode positrons are identified by signatures such as D5D7 and D5D6D8.

The instrument's efficiency for identifying positrons has been established by calibration and calculation. For D5 positrons it is ~ 1.6×10^{-2}, for D0 positrons ~ 2.8×10^{-3}. The principal background source of events with positron-like signatures is double-Compton-scattered γ-rays, a possible example of which is illustrated in Figure 1.

CALTECH ELECTRON/ISOTOPE SPECTROMETER
POSITRON DETECTION

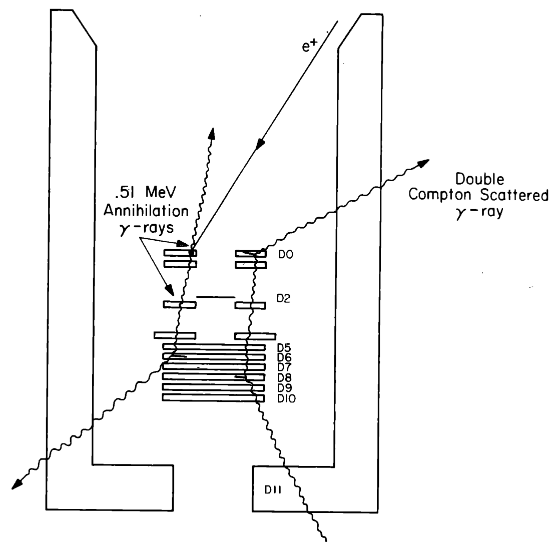

Fig. 1. Cross section of the Caltech Electron/Isotope Spectrometer illustrating one mode of positron detection and a possible background event due to a double-Compton-scattered γ-ray.

During quiet times we measure a very constant rate of positron-type events in both Narrow and Wide Geometry, a significant fraction of which is known to be due to double-Compton-scattered γ-rays. A significantly enhanced flux of positrons during a solar flare would result in a temporary increase in the rate of positron-type events above this quiet-time level. (Hurford et al., 1973c)

3. <u>Solar Flare Observation</u>. We have selected the four largest solar-particle events during the period 1 October 1972 to 1 February 1973 to look for solar-flare positrons. These events are listed in Table II, where the date refers to the onset of the particle event at earth. No statistically significant increases in the rate of positron-type events were observed in either the Narrow or Wide Geometry modes during any phase of these events, allowing only upper limits to be placed on the solar-flare positron flux. In order to compare these upper limits with the number of electrons and protons observed, we have integrated the electron and proton fluxes observed in our instrument over 12 hour time periods beginning with the onset of the particle event, and extending to include at least 90% of the total number of flare particles observed. The results of this analysis are summarized in Table II, where the upper limits to the positron flux are at the 95% confidence level.

4. <u>Discussion</u>. The results in Table II indicate that positrons in the 0.2 – 2 MeV range make up at most a small fraction of the total solar-flare electrons observed in these events. Summing over four events, we find

TABLE II

SOLAR PARTICLE FLUENCES

Event	Measurement Period	Protons (1.2-27.5 MeV) ($cm^{-2}sr^{-1}$)	Electrons (0.2-2 MeV) ($cm^{-2}sr^{-1}$)	Positrons (0.2-2 MeV) ($cm^{-2}sr^{-1}$)	$\frac{e^+}{e^+ + e^-}$
29 Oct 1972	48 hr	$\sim 3 \times 10^8$	$\sim 8 \times 10^6$	$< 8 \times 10^4$	$< 10^{-2}$
25 Nov 1972	36 hr	$\sim 2 \times 10^5$	$\sim 2 \times 10^6$	$< 2 \times 10^3$	$< 10^{-3}$
28 Nov 1972	48 hr	$\sim 10^6$	$\sim 4 \times 10^5$	$< 5 \times 10^3$	$< 1.3 \times 10^{-2}$
16 Dec 1972	48 hr	$\sim 10^5$	$\sim 9 \times 10^5$	$\leq 2 \times 10^3$	$< 2 \times 10^{-3}$
Sum over 4 events:		$\sim 3 \times 10^8$	$\sim 1.1 \times 10^7$	$< 7 \times 10^4$	$< 6 \times 10^{-3}$

$e^+/(e^+ + e^-) < 6 \times 10^{-3}$ at the 95% confidence level. Note, however, that solar flare positrons would be expected to bear a generic relationship to solar-flare nuclei rather than electrons.

We now compare these results to the calculations of R&L (1973). These authors have calculated the yield of positron emitters (Table I) per second for various solar-flare proton rigidity spectra, normalized to a solar number-density of 1 cm^{-3} and to 1 accelerated proton with rigidity greater than zero. We consider positron production over the time required for 30 MeV protons to traverse 1 g/cm^2, a pathlength consistent with typical solar-flare $^3He/^4He$ values (L&R, 1967, Hsieh et al., 1970, Garrard et al., 1972, Anglin et al., 1972). For an exponential rigidity spectrum $N(P) \propto \exp(-P/P_0)$, we find $N(P>0) \sim 4 \times 10^9$ $cm^{-2}sr^{-1}$ and $P_0 \sim 25$ MV for the event of October 30, the largest event reported on here. Using these numbers and the "thin target model" of R&L (1973), and assuming that all positrons escape and propagate to Earth in a manner similar to the protons, we calculate a positron fluence of $\sim 6 \times 10^2$ compared to our upper limit of 8×10^4 $cm^{-2}sr^{-1}$ for this event.

The relatively soft proton spectrum of the October 30 event is not especially favorable for positron production. In order to estimate positron yields in more favorable situations, we consider the 4 August 1972 event which occurred 2 months before the launch of IMP-7. Using proton data of Kohl and Bostrum (1972) and $P_0 \sim 65$ MV (R&L, 1973) we find a peak intensity at Earth of $J_{\beta^+} \sim 2$ $cm^{-2}sr^{-1}sec^{-1}$, under the same assumptions as above. This flux is more than 100 times our quiet-time upper limits to the 0.16-1.6 MeV positron flux (Hurford et al., 1973c) and would have been detectable at our level of sensitivity. Note, however, that pathlengths $\ll 1$ g/cm^2 or inefficient positron escape from the sun would lower these estimates.

5. Conclusion. Although the results presented here indicate that solar-flare positrons are rare, they do not as yet provide a test for theoretical calculations of solar-flare positron yields. However, future identification of solar-flare positrons in very large solar events may be possible, and

simultaneous measurements of solar γ-rays, positrons, and rare isotopes of secondary origin would provide crucial information for studying solar-flare regions, acceleration processes, and particle propagation.

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